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Technical Approach for Coupled Reliability-Durability Assessment of Army Vehicle Sub-Assemblies

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ABSTRACT

The US Army is seeking to advance simulation methods for assessing the performance and reliability of ground vehicles. The reliability is defined as the probability that the Army vehicle performs its function over a specified period of time and under specified loading conditions; it can be viewed as a measure of successful performance of the component, sub-assembly and eventually whole vehicle. For the structural reliability calculation to be meaningful, it must be coupled with durability evaluation. The durability describes the ability of the structure to endure or resist applied loading. Maximum benefit would be obtained when both the reliability and durability are maximized. Such an outcome is highly desired, especially if it is achieved at low cost and low weight.

INTRODUCTION

The US Army is seeking to advance simulation methods for assessing the performance and reliability of ground vehicles. The reliability is defined as the probability that the Army vehicle performs its function over a specified period of time and under specified loading conditions; it can be viewed as a measure of successful performance of the component, sub-assembly and eventually whole vehicle. For the structural reliability calculation to be meaningful, it must be coupled with durability evaluation. The durability describes the ability of the structure to endure or resist applied loading. Maximum benefit would be obtained when both the reliability and durability are maximized. Such an outcome is highly desired, especially if it is achieved at low cost and low weight.
The objective of the present work is to describe a formal computational strategy for accurate evaluation of reliability and durability of vehicle components. Figure 1 shows a block diagram of the proposed strategy to achieve the desired structural performance. The computational capability must be able to account for: material degradation at increased stress levels, strength degradation at increased life cycles (S-N curve), environmental degradation, variability in material properties, thermo-mechanical-fatigue loading, and fabrication defects (e.g., cracks) and in-service conditions. As depicted in Figure 1, the reliability analysis relies on accurate modeling of uncertainties, low and high fidelity probabilistic methods and optimization to maximize the reliability. The durability evaluation combines progressive failure analysis with finite element and damage tracking and fracture. The durability analysis of notched or un-notched parts must include any structural defects and material degradation factors. In this paper, durability and reliability results obtained from the evaluation of a double A-Arm sub-assembly under spectrum loading condition are summarized and discussed. The analysis also includes effect of variability in material properties, loading and manufacturing.

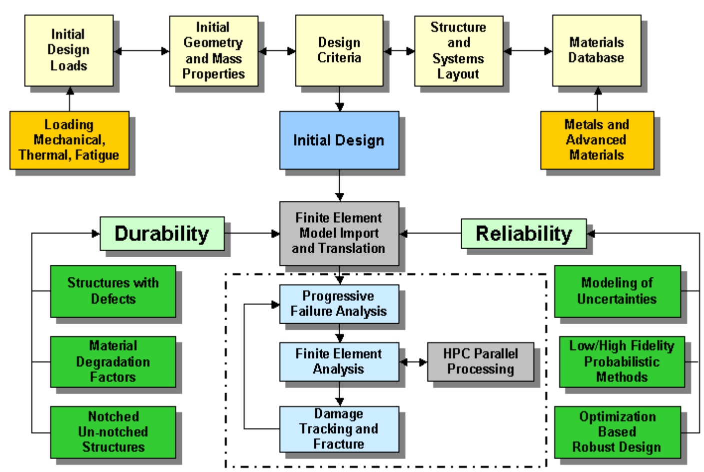

Figure 1. Strategy for Coupled Reliability-Durability

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DESCRIPTION OF GENOA METHODOLOGY

PROGRESSIVE FAILURE ANALYSIS (PFA)

PFA in GENOA takes a full-scale finite element model and accounts for the average material failure at the microscopic level. Material properties are updated for all iterations, reflecting any changes resulting from damage or crack propagation. The GENOA hierarchical approach (Figure 2) allows integration of a wide range of specialized programs, from micro to macro, into an existing verified progressive failure and probabilistic analysis tool [1,2]. This makes it possible to accomplish synthesis of a variety of composite materials and structures based on progressive failure analysis and virtual testing to predict structure/component safety based on the physics and micro/macro mechanics of materials, manufacturing processes, available data, and service environments. This approach takes progressive damage and fracture processes into account and accurately assesses reliability and durability by predicting failure initiation and progression based on constituent material properties.

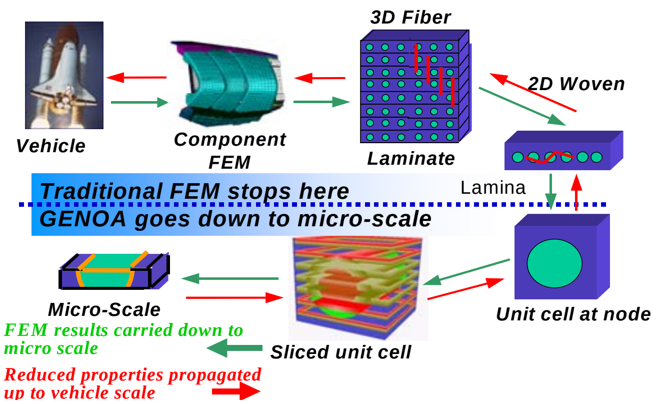


Figure 2. Hierarchical distribution of damage, stress, and strain from the macro to micro mechanical level.

The life prediction code utilizes and integrates: (a) finite element structural analysis, (b) micro-mechanics, and fracture mechanics options, (c) damage progression tracking, (d) probabilistic risk assessment, (e) minimum damage design optimization, and (f) material characterization codes to scale up the effects of local damage mechanisms to the structure level to evaluate overall performance and integrity. A significant advantage of using a life prediction tool in the durability and damage tolerance is that the number of experimental tests at the component and substructure levels can be substantially reduced and experimental testing that is done made more efficient and effective.

DETERMINSITIC DURABILITY AND DAMAGE TOLERANCE EVALUATION

The A-Arm suspension component and the sub-assembly were analyzed with GENOA's progressive failure analysis module PFA to determine the damage initiation and fracture loads and cycles for quasi-static and fatigue loading, respectively.

RESULTS: DURABILITY AND RELIABILITY EVALUATION OF A-ARM COMPONENT

A finite element model of a 'Control Arm' of a double A-Arm Suspension sub-assembly was evaluated with three different load case conditions. The first model represents one component of the sub-assembly. The progressive failure analysis was conducted with GENOA for three separate load cases. The geometry of the Control Arm is shown in Figure 3.

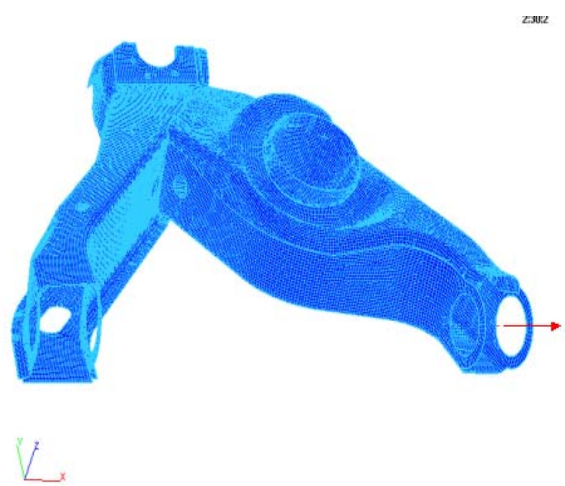


Figure 3. Finite Element Model of Control Arm with Load Direction for Load Case # 1

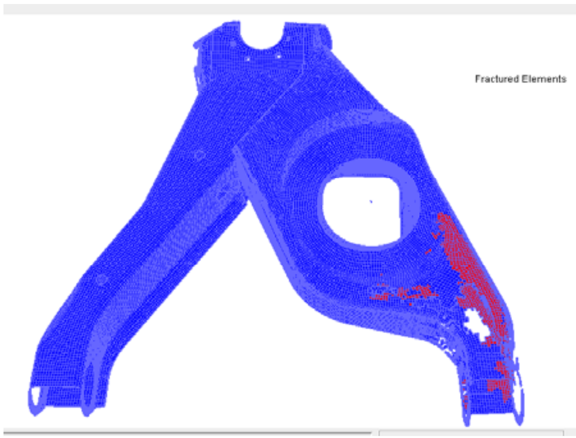


Figure 4. Fracture of Control Arm at Ultimate Load of 12,600 lb

Mechanical properties (including non-linear stress-strain data from Mil-HDBK-5H) for low-alloy steel (AISI 8630) were used in the analysis. The objective was to demonstrate a process for determining the load carrying ability of the A-Arm component. Figure 3 shows the load direction for Load Case Number 1. The PFA increases the load accounting for geometric and material non-linearities until structural fracture. Figure 4 shows the structural fracture of the control arm at 12,600 lb. The failure was due to stress exceeding the strength in the longitudinal and transverse directions. During the load increase process, the code re-meshes the model as the elements start failing [Ref 3 to 6]. Table 1 shows the failure loads for the various load cases. Note that load cases number 2 and 3 are similar to load case 1 with the exception that the loads are applied in the Y and Z directions, respectively.

Table 1. Comparative Evaluations of Damage and Fracture Loads for the Control Arm (Based on Three Independent Load Cases)

Force Magnitude (lb)	Load Case 1	Load Case 2	Load Case 3
First Damage Initiation	7,480 lb (in X dir.)	25,250 lb (in Y dir.)	4,988 lb (in Z dir.)
Ultimate (Fracture Load)	12,600 lb (in X dir.)	31,560 lb (in Y dir.)	13,500 lb (in Z dir.)
Execution Time (CPU sec)	3,332	4,126	3,417

Table 2. Probabilistic Modeling of the Control Arm (Load Case 1)

Primitive Variable	Mean Value	Standard Deviation	Distribution Type
Linear Elastic Modulus (psi)	29.0E06	2.9E06	Normal
Rupture Strength (psi)	95,000	9,500	Normal
Stress-Strain Curve	1.0	0.10	Normal
Thickness of Main Arm – Bottom (in)	0.135	0.0135	Normal

The fracture load of the control arm was assessed probabilistically based on assumed probabilistic distributions, mean values, and standard deviations as shown in Table 2. The primitive variables considered were: linear elastic modulus, rupture strength, stress-strain curve, and the thickness of the main arm (bottom), which is the same arm where the load is applied. The objective of this particular simulation is to demonstrate a process through which the fracture load of the control arm can be quantified probabilistically. The results obtained from the probabilistic simulation are shown in Figures 5 and 6, respectively. The cumulative distribution function is plotted with the fracture load in Figure 5. The analysis indicates that the maximum reliability (0.9999) will be achieved if the load is kept under 1,600 lb. The sensitivity analysis results show that the rupture strength is the dominant uncertainty followed by the thickness and stress-strain curve.

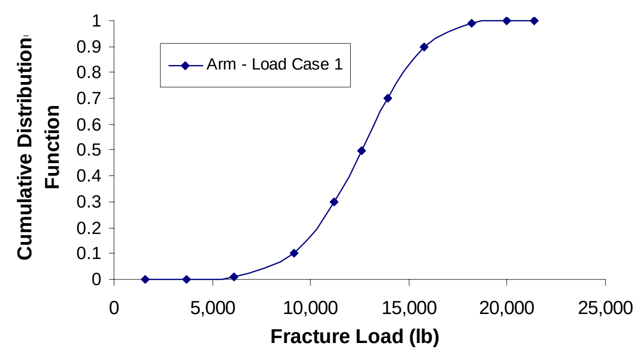


Figure 5. Probabilistic Fracture Load of Control Arm (Load Case 1)

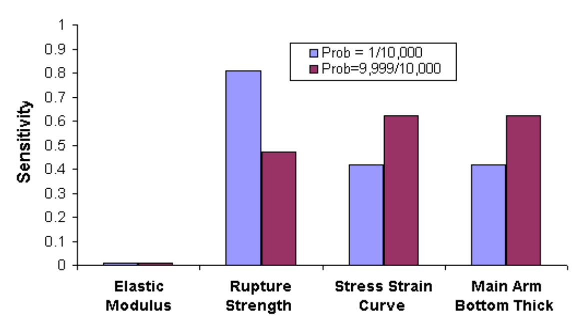
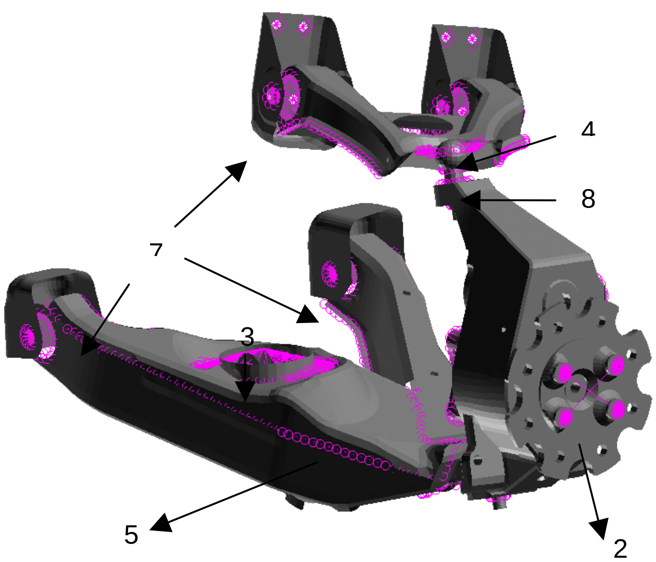
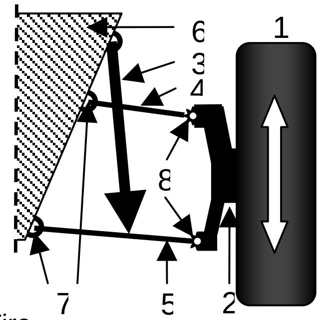


Figure 6. Probabilistic Sensitivities of Random Variables

RESULTS: DURABILITY AND RELIABILITY EVALUATION OF DOUBLE A-ARM SUB-ASSEMBLY

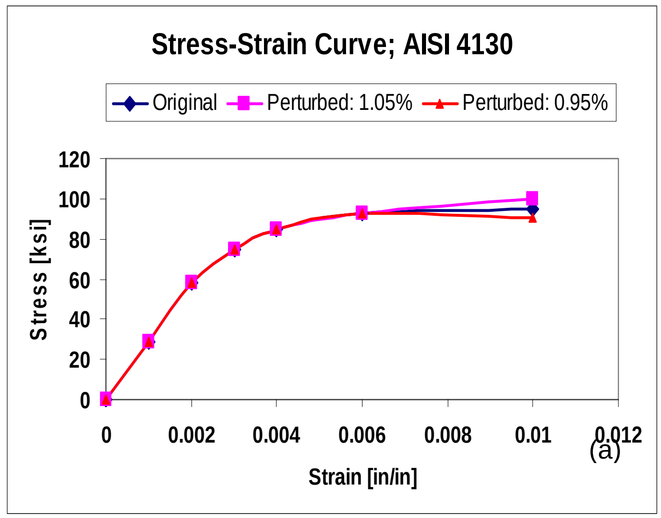
Reliability study was conducted on front wheel double A-Arm suspension system (see Figure 7) of High Mobility, Multipurpose Wheeled Vehicle, also known as HMMWV. The double A-Arm suspension has earned its reputation for its effectiveness and longer life and is therefore best choice for the HMMWV. These vehicles are used for various purposes: transportation of crew, ammunition and other such critical purposes. They are driven through all topographical terrains such as rocks, sand, paved roads, and even shallow waters and different weather conditions such as cold, warm and humid conditions. These environmental conditions subject the double A-Arm to its ultimate limits. It is highly desirable to measure the factors that affect the optimum functioning of the suspension system. Identifying these parameters can help improve the suspension system for optimized performance during hostile environment (e.g. battle field).





1. Tire
2. Wheel Spindle
3. Spring
4. Upper A-Arm
5. Lower A-Arm
6. Chassis
7. Hinge Joint (out-of-page rotation allowed)
8. Ball Joint (all rotations

Figure 7. Finite Element Model and Schematic of the Double A-Arm Suspension



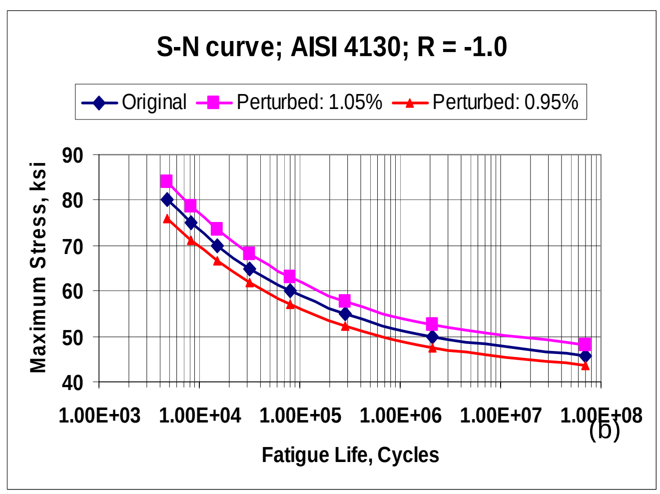


Figure 8. Engineering Stress-Strain Curve (a) and SN curve (b) for AISI 4130 Along With Perturbed Strength Values And Stress Values Corresponding to 5% Coefficient of Variation

A preliminary study was conducted by perturbing the material properties by 5%, as shown in Figure 8. These perturbations relate to reliability evaluation of the sub-assembly (presented later).

Finite Element Analysis: A quasi-static fatigue analysis was performed on the sub-assembly using NASTRAN as the FEA solver with GENOA. The model contains several types of elements including solid and shell. For a preliminary study, only one kind of material was used to model the whole sub-assembly. Ten failure criteria were selected that check for damage due to tensile and shearing of the several parts. Spectrum loading feature in GENOA was then applied to model the loading and boundary conditions.

Model: The model was meshed with 45533 nodes (68908 elements). Several different types of solid and shell elements are used to fully mesh the 3D model. The sub-assembly model contains total of 22 isolated parts and are connected using RBE2 elements available in NASTRAN, also supported by GENOA. The hinge and ball joints shown in Figure 7 are defined by tying two nodes located at the same location, but connected to different parts using RBE2 elements. For hinge joints, all degrees of freedom were constrained except for rotational degree of freedom relevant to the axis of rotation. Similarly, for ball joints, all translational degrees of freedom were constrained with respect to the nodes tied to the parts.

Material Properties: For simplicity, AISI 4130 steel was used as material in the analysis. The material properties were taken from the MIL HANDBOOK and are shown in Figure 8a (blue curves). Due to the nature of the spectrum loading applied, S-N curve for a stress ratio of -1 was used to estimate the fatigue life of the suspension system. To model the environmental effects, the material properties were perturbed by ±5%, as shown in Figure 8. In addition, in order to optimize the performance of the suspension system the thickness of the hinge assembly that connects the A-arms to the chassis of the HMMWV was also varied by ±5%.

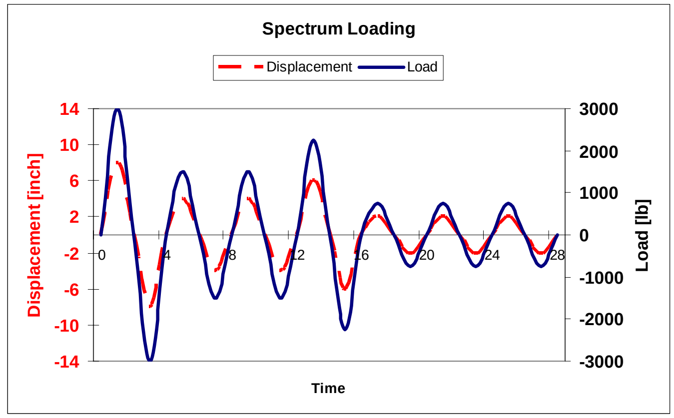


Figure 9. Spectrum Loading Chosen to Model The Displacement of the Tire and Corresponding Spring Force For The Finite Element Analysis

Boundary and Loading Conditions: Boundary conditions and loading conditions used by the Army research team were not available to us at the time of evaluation. Therefore, based on existing literature typical boundary conditions and loading were incorporated to demonstrate the technology. The boundary and loading conditions were applied assuming the relative motion of the wheel with respect to the chassis; therefore, all degrees of freedom for joints that connect the upper and lower A-arms to the chassis were fixed. On the other hand, spectrum loading was applied to model both the spring load and the displacement boundary conditions on the lower A-arm and the wheel spindle, respectively. The displacement cycles were chosen assuming that the wheel begins by climbing an 8 inch high rock once then descending the rock and an 8 inch deep pit once, and similarly over 4 inch rocks twice, then 6 inch rock once, and finally over 2 inch rocks thrice again. The spring is assumed to have linear stiffness (375.0 lb/in); hence the corresponding load varied according to the displacement of the joint where the spring is connected to the hook on the lower A-arm. The spring load varied between 0 lb to 3000 lb corresponding to the 0 inch to 8 inch displacement, as shown in Figure 9 (blue curve).

Simulation Results: In order to perform probabilistic study, several simulations were repeated beginning with original variables followed by perturbed parameters: strength, S-N curve, and thickness of the connectors. Unperturbed simulation results, as shown in Figure 10, indicate that the damage initiated in the metallic hinge piece that connects the upper A-arm with the chassis of the HMMWV at approximately 20,000 cycles. Local material failure was produced because the stress in the longitudinal, transverse and shear directions exceeded the allowable strength.

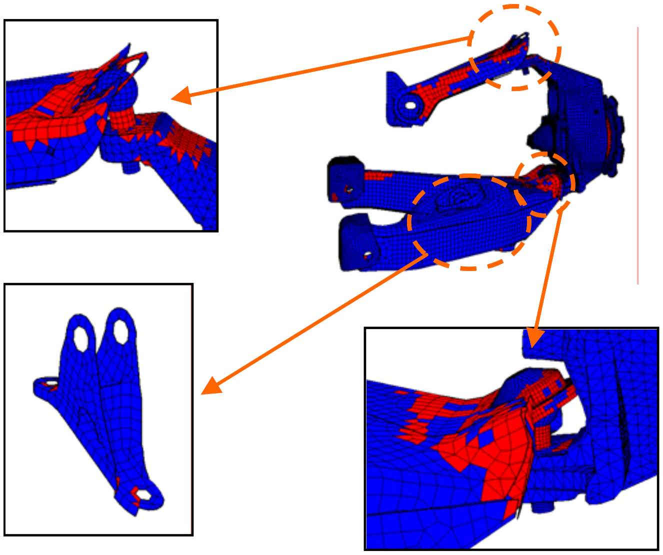


Figure 10. Damage predicted by GENOA using NASTRAN as the FE solver at 20,000 cycles (in the hinge joint support)

Figures 10 and 11 also show the final damage and the corresponding 'percent damage volume' with respect to 'fatigue cycles,' respectively. The simulation indicated that the reason for damage initiation in the connector of the spring arm of the control A-arm was the spring load that applies both translational as well as rotational load at the hinge joint. While the rotational force resulted in zero moment due to the hinge joint, the translational force ended up damaging the upper and lower control arms (see Figure 10). These damages (Figures 10 and 11) occur when the stresses exceed the limits (see Figure 12) due to movement of the wheel spindle (Figure 13).

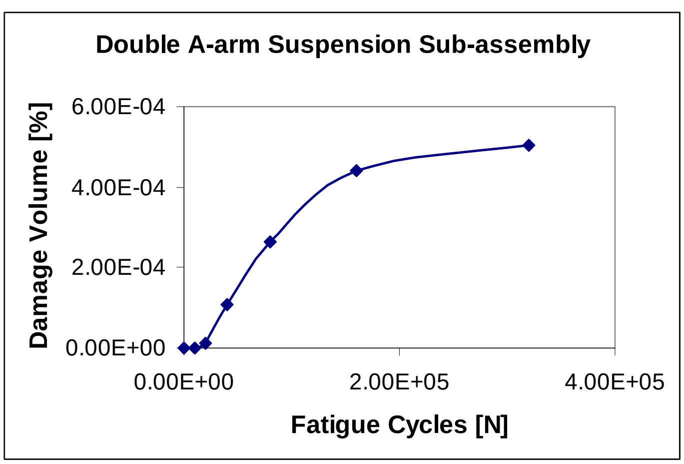


Figure 11. increase in damage volume of the whole sub-assembly with respect to the fatigue cycles

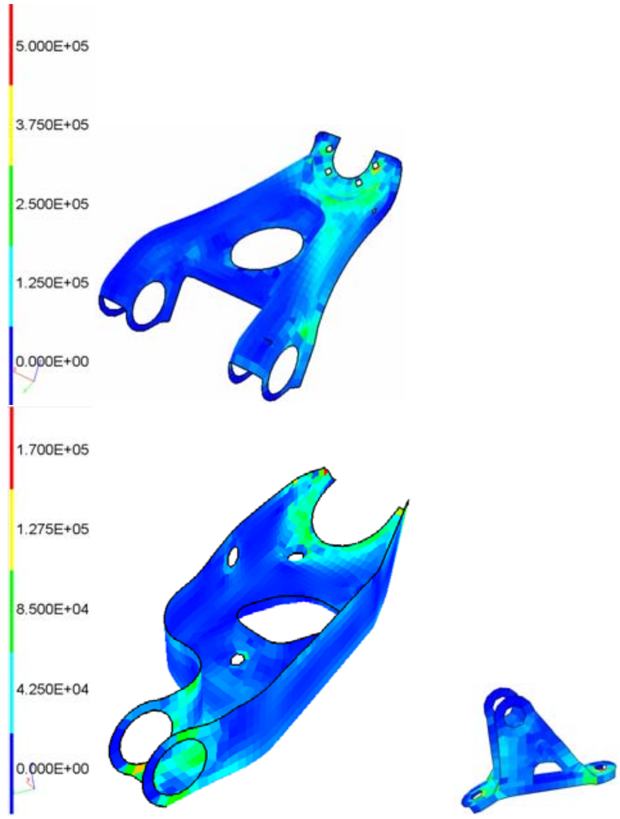


Figure 12. Overall Von Misses Stresses at 20,000 Cycles (a) Upper Control Arm, and (b) Lower Control Arm and Spring Support

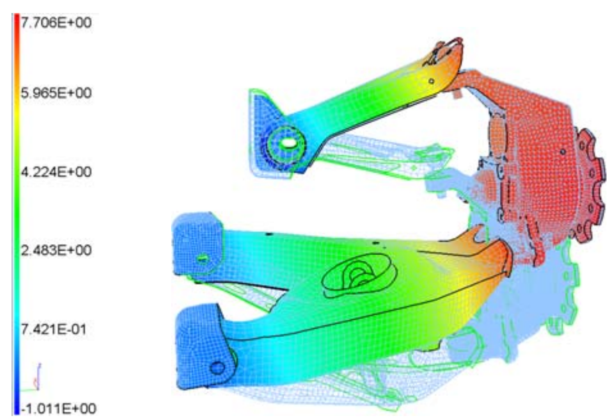


Figure 13. Overall Deterministic Structural Deformations at 20,000 Cycles

Suspension Unit Reliability Evaluation: Furthermore, the reliability of the suspension unit was evaluated probabilistically using assumed random variables as shown in Table 3. The random variables selection included: Maximum strength (S-N curve), LCA joint thickness, maximum dynamic load, and ambient temperature. The response function evaluated is the number of cycles that would produce the first material damage (failure). The distribution types and standard deviations were also assumed. Figure 14 shows the cumulative distribution function for the number of mechanical cycles that would produce the first material failure. If the number of cycles were kept under 472, the reliability of the unit would be 0.99.

Table 3. Probabilistic Modeling of the Suspension Unit

Random Variable	Mean Value	Standard Deviation [10% COV]	Distribution Type
Max Strength (S-N) Curve	95000 psi	9500 psi	Normal
LCA Joint Thickness	0.12 in	0.012 in	LogNormal
Maximum Dynamic Load	1	0.1	Normal
Temperature	70 F	7	Normal

The scatter obtained from the probabilistic analysis is presented in Figure 14. For a probability of occurrence varying from 0.00413 to 0.9987, the number of damage elements varied from 0 to 200. If the number of damage elements is kept at 0, the reliability of the structure would be 0.9959, i.e., 4 failures in 1000 parts built. The analysis was repeated using a coefficient of variation (COV) of 30% on the temperature only while keeping all other COVs at 10%. The analysis was repeated with 30% COV for the temperature to assess the change in the reliability. Here we find, as shown in Figure 14, the reliability drops from 0.9959 to 0.9927. The drop in the reliability as a result of larger scatter in the temperature translates into 8 parts failing in a batch of 1000.

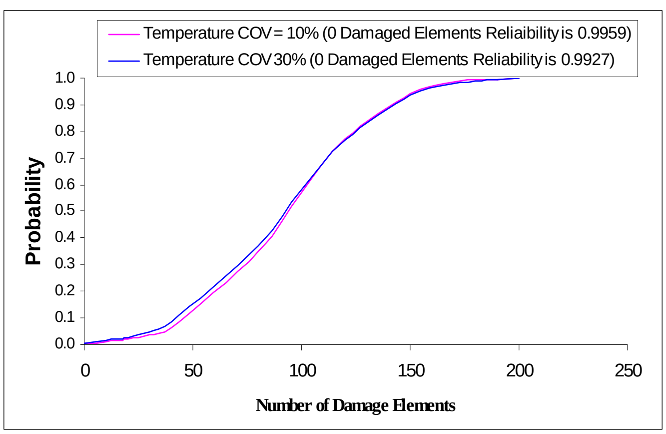
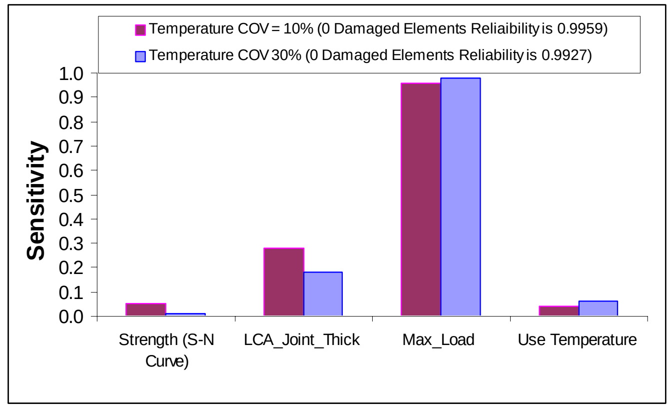
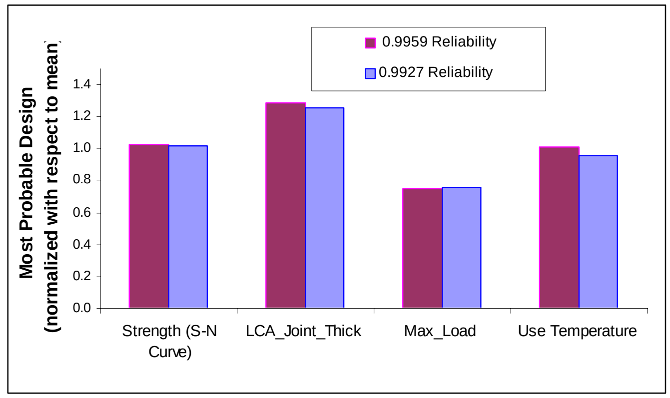


Figure 14. Probabilistic Scatter (Damaged Elements)



(a)



(b)

Figure 15. (a) Probabilistic Sensitivities of Random Variables (b) required design to prevent material damage.

The sensitivity analysis presented in Figure 15 indicates that the dominant uncertainties are in the order of importance as follows: the maximum dynamic load (90% sensitivity) followed by the lower control arm joint thickness (30% sensitivity). The temperature and the maximum strength on the S-N curve have the least effect on the number of damaged elements. The sensitivity analysis indicates that reducing the scatter in the load will reduce the scatter in the number of damaged elements. Another note to make is that the relative sensitivity of the temperature has doubled when the COV was increased from 10% to 30%. The outcome of the reliability analysis would be different if actual sub-assembly loads were applied. Assumed cyclic loads were discussed previously (Figure 9).

CONCLUSION

The US Army is seeking to advance performance and reliability prediction methods of ground vehicle systems. The objective was to demonstrate a concept for tools required to assess the reliability of Army vehicle components. Alpha STAR Corporation (ASC) was able to successfully demonstrate that the combined use of physics-based progressive failure analysis with computer aided engineering software and reliability methods is capable of predicting performance and reliability of Army vehicle components and sub-assemblies. In summary, following tasks were accomplished:

1) Evaluated durability and reliability of a control arm of a double A-Arm suspension unit in presence of multiple static loading conditions.

2) Evaluated durability and reliability of a double A-Arm suspension sub-assembly in presence of mechanical fatigue loading.

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